Probing the Early Universe with Galaxy Clustering

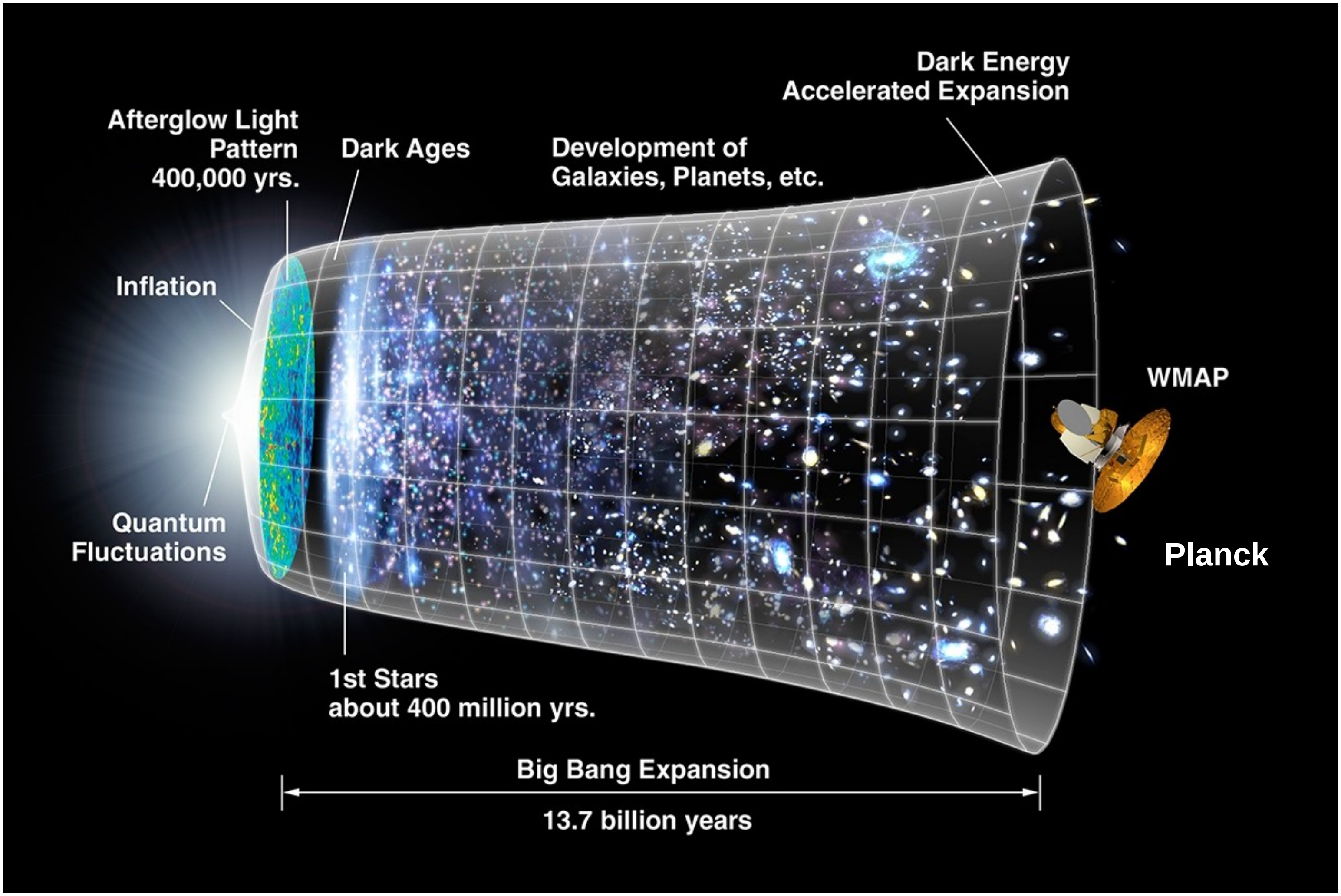
Fabian Schmidt

with Francis Cyr-Racine, Vincent Desjacques, Donghui Jeong, Marc Kamionkowski, Emiliano Sefusatti

Berkeley TAC Seminar, 12/6/11

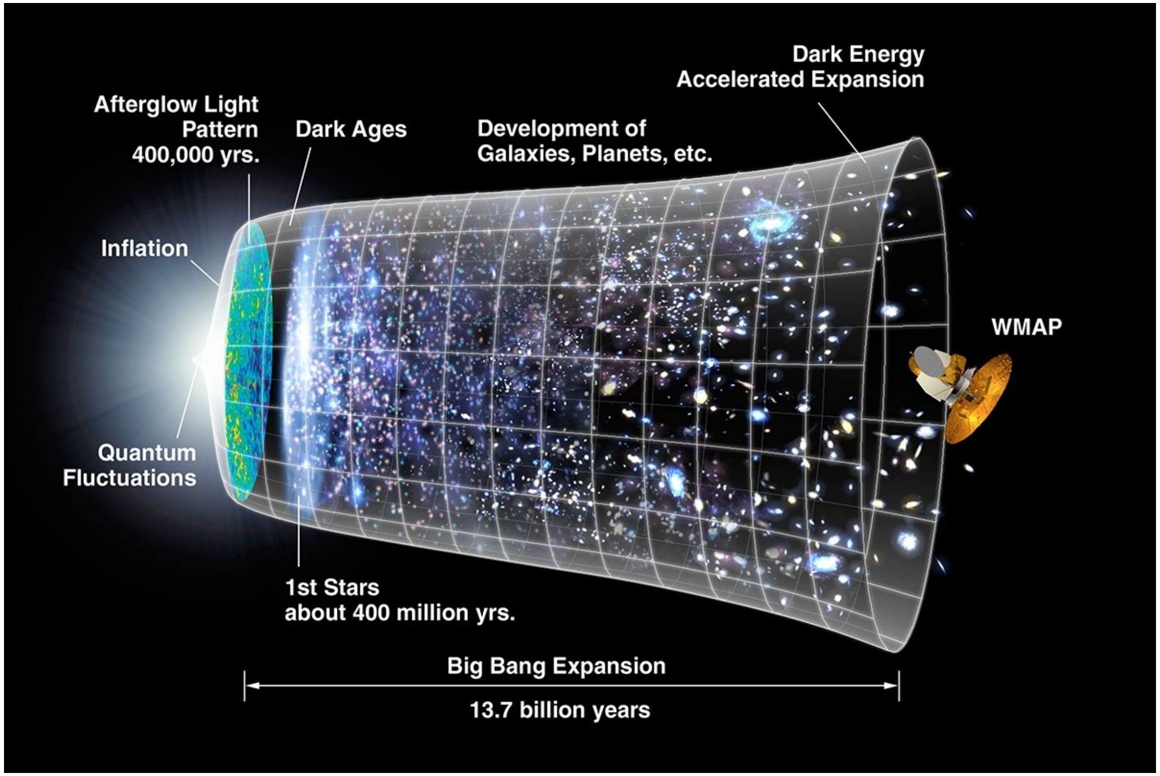
Introduction

- Pictorial history of the Universe



Introduction

- What we would like to know
  - Expansion history H(z) of background Universe
  - Origin and evolution of perturbations



Perturbations

- Origin of initial density perturbations in the Universe ?
  - Inflation - most popular scenario
  - Determining physics & energy scale (10^3 – 10^{19} GeV) of inflation is (one) holy grail of cosmology

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  - CMB -> snapshot at z~1100
  - Subsequent evolution determined by gravity
    --> probe dark matter, *General Relativity*

Perturbations

- Origin of initial density perturbations in the Universe ?

Focus of this talk

  - Inflation - most popular scenario
  - Determining physics & energy scale (10^3 – 10^{19} GeV) of inflation is (one) holy grail of cosmology

- Evolution of perturbations
  - CMB -> snapshot at z~1100
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    --> probe dark matter, *General Relativity*

Aside: a new approach to weak lensing

- Standard approach: shear γ
  - measured through galaxy shapes
- Idea: measure magnification (convergence κ)
  - using galaxy fluxes/sizes
- Additional **signal-to-noise / lensing information**
  - κ and γ measure *different quantities:*

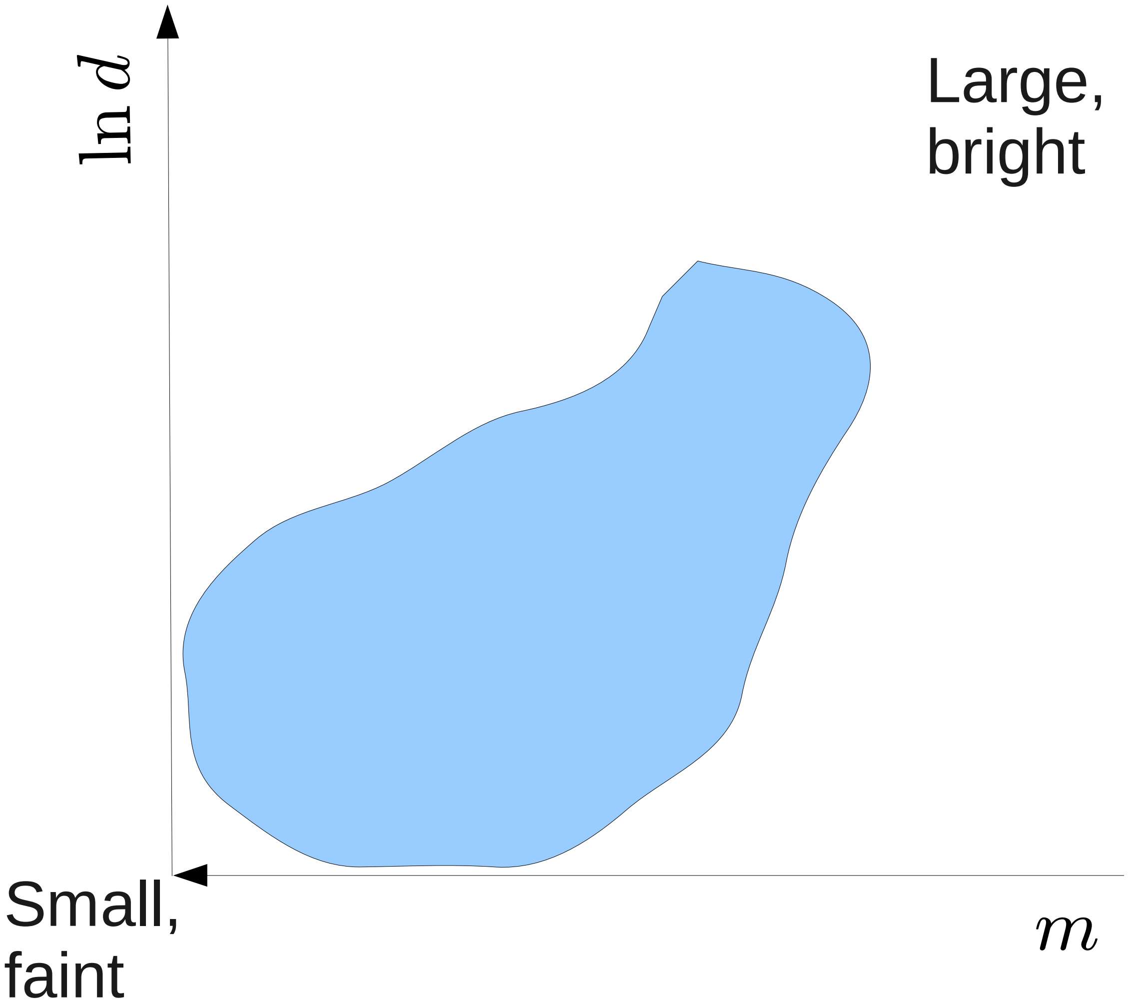
$$\kappa(\vec{r}) = \Sigma(\vec{r})/\Sigma_{\rm crit}$$

$$\gamma(r) = \left(\bar{\Sigma}(< r) - \Sigma(r)\right)/\Sigma_{\rm crit}$$

Σ: projected surface mass density

Jain 02; FS et al; 1111.3679

Magnification effect



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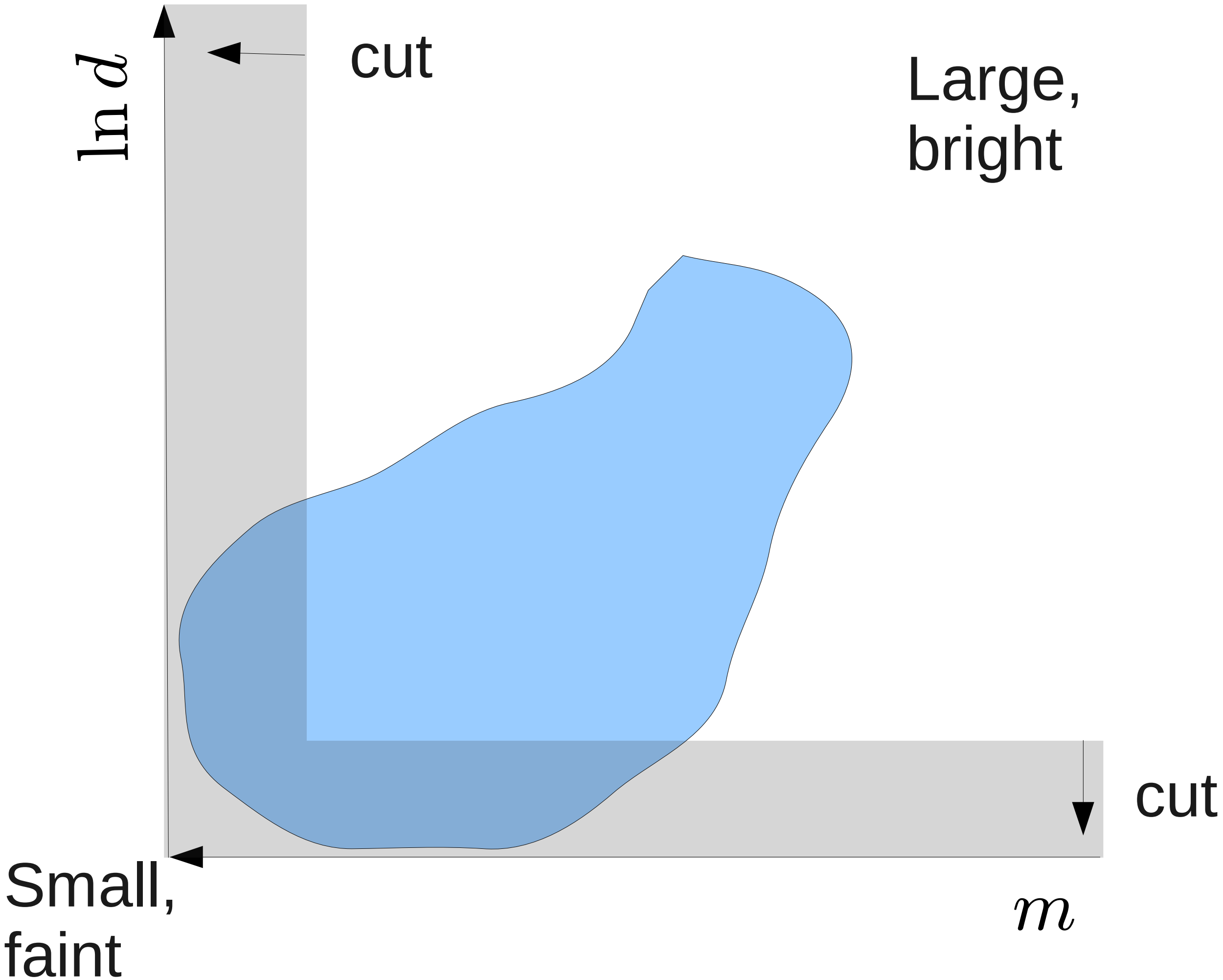

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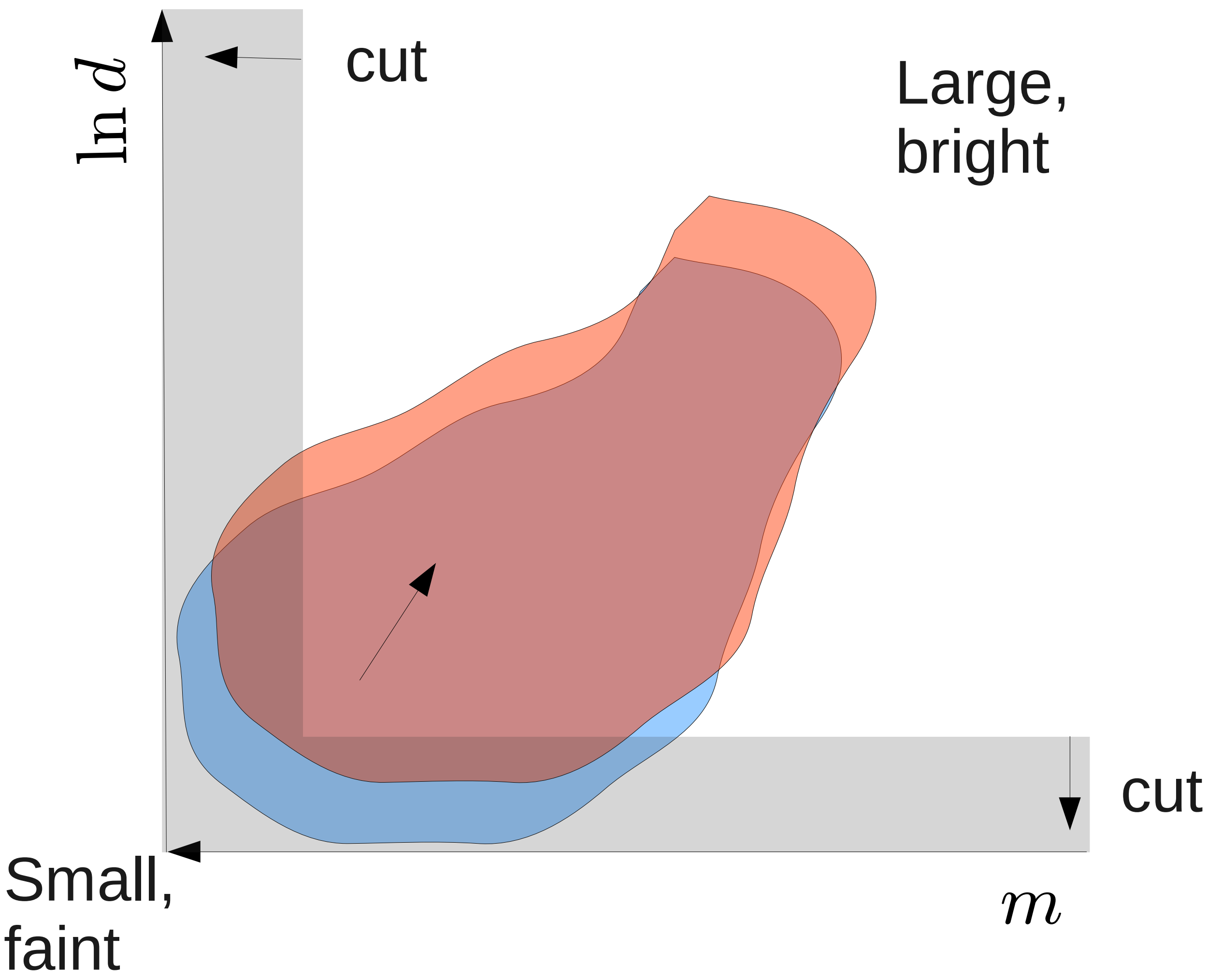

Sizes:

$$\ln d = \ln d_0 + \eta\,\kappa$$

Fluxes:

$$m = m_0 + q\,\kappa$$

$$\eta \approx 1; \quad q \approx -2.1$$

Estimator for Σ (κ)

- Approximate unlensed distribution as bivariate Gaussian in ln d, m

FS et al; 1111.3679

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  - $\rightarrow$ Gaussian likelihood for κ
    - *Here: d = RRG variable width Gaussian filtered*
      m = SExtractor F814w
    - *Both from Hubble ACS data*

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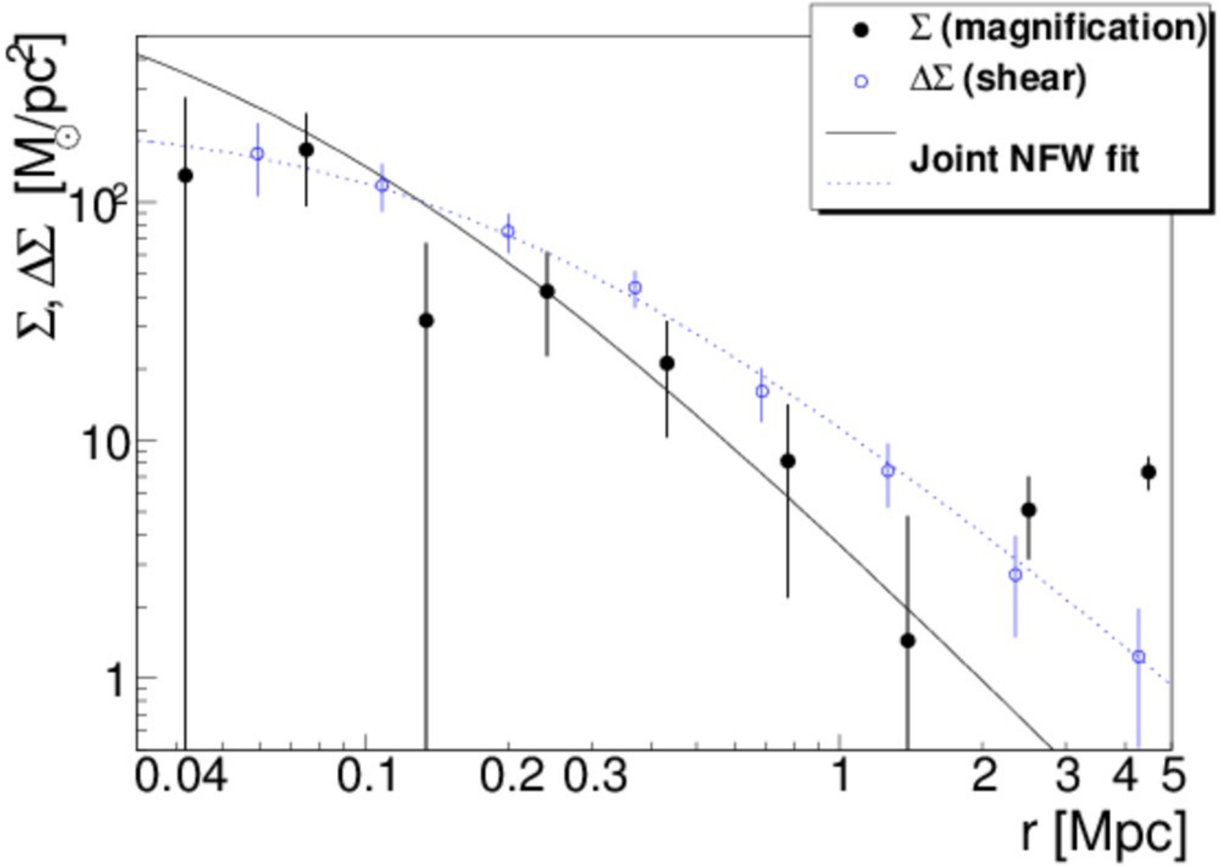
- Estimator does *not use* number density of sources

FS et al; 1111.3679

Magnification around X-ray groups in COSMOS

- Stacked group sample z=0.2-0.6



Detection significance:
~4σ within r < 1 Mpc
~40% of shear

FS et al; 1111.3679

Inflation

- Phase of exponential expansion
  - “almost-de Sitter”, driven e.g. by $V(\phi)$
  - Solves problems of flatness and “superhorizon” correlations

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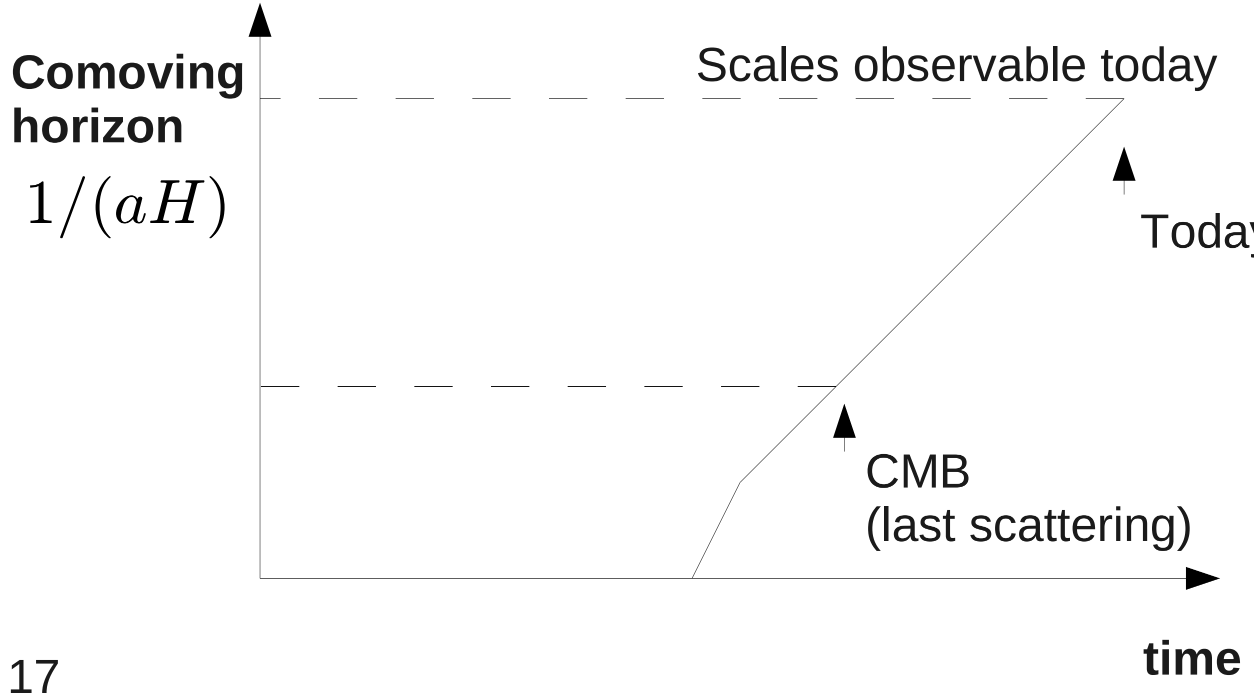

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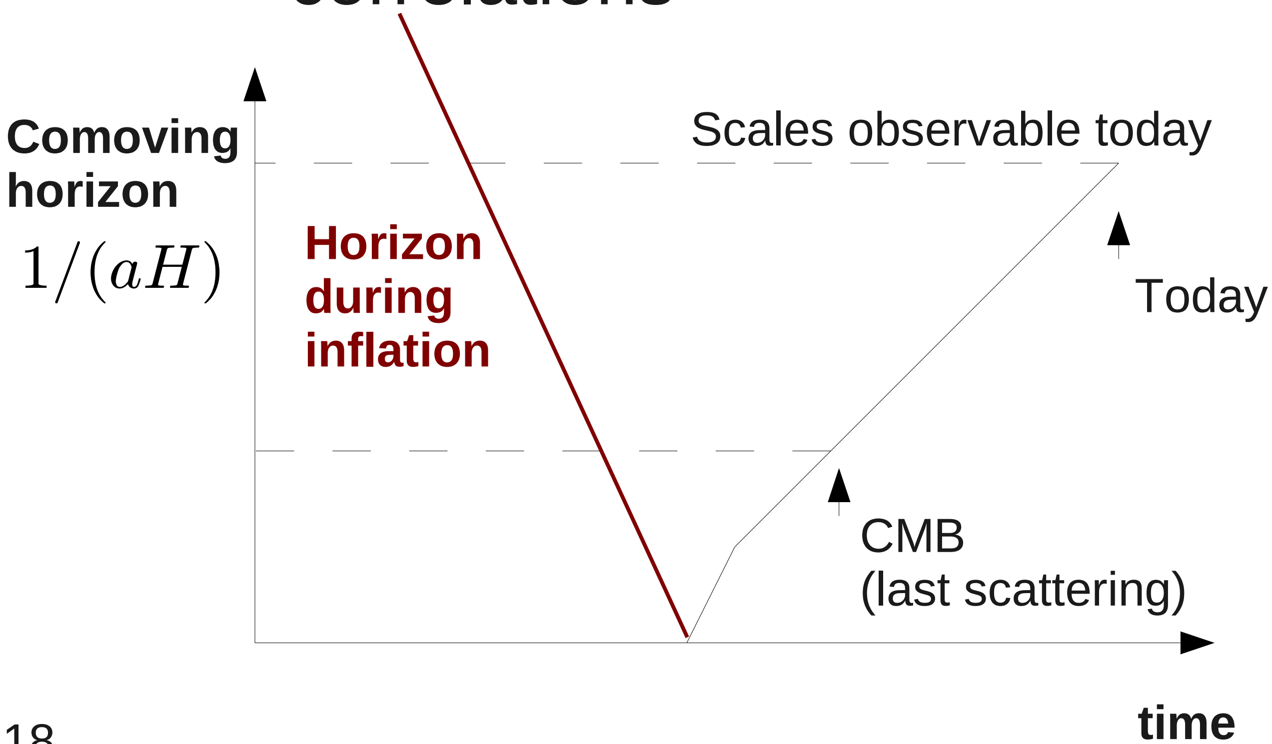
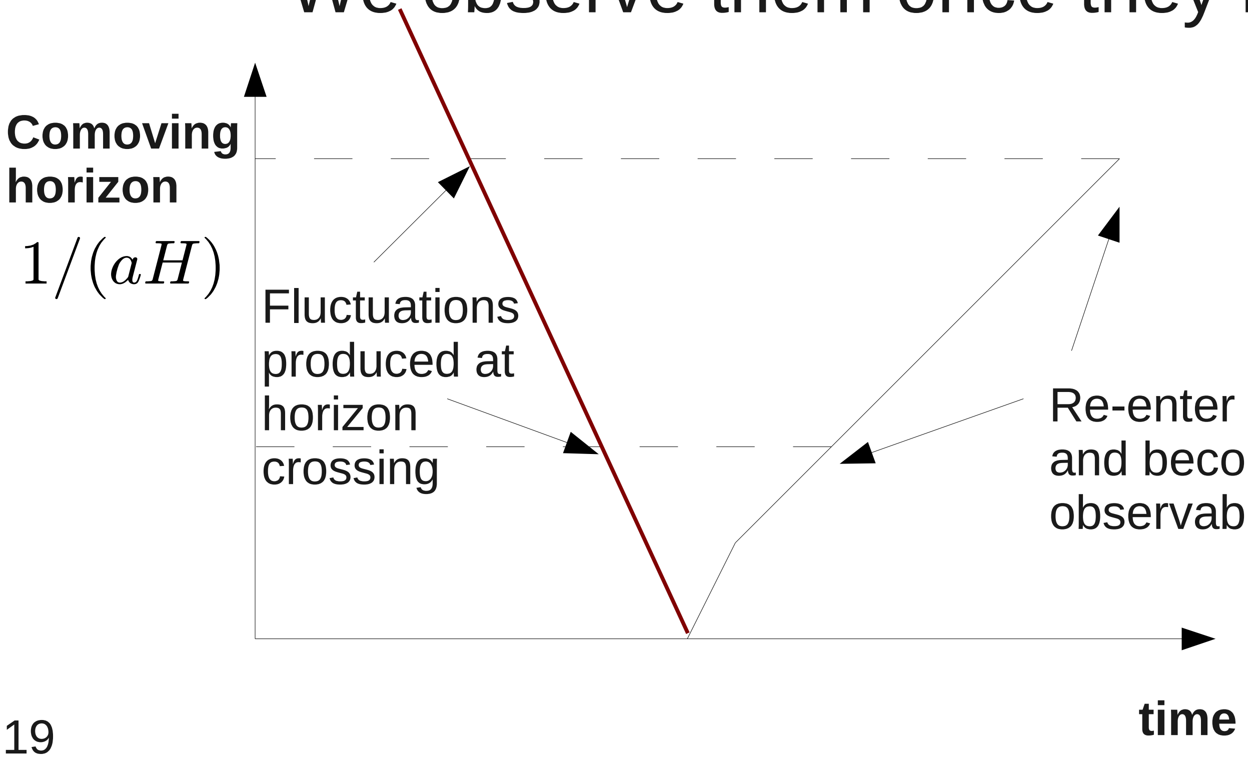


Perturbations from Inflation

- Quantum fluctuations “freeze” once outside the horizon
  - Analogous to Hawking radiation
  - We observe them once they re-enter the horizon



Perturbations from Inflation

- Generic prediction:
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  - smooth, *almost* scale-invariant power spectrum (two-point correlation)

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- Generic prediction:
  - *almost*-Gaussian fluctuations
  - smooth, *almost* scale-invariant power spectrum (two-point correlation)
- All information* on inflation is encoded in *departures* from Gaussianity & scale-invariance
  - So far: one number $n_s - 1 \approx -0.04 \pm 0.01$

* in scalar modes. There might be detectable gravitational waves.

Perturbations from Inflation

- Departures from Gaussianity (= non-Gaussianity) in principle contains much more information
  - Amount and form of NG depends on detailed physics of inflation:
    - Inflaton interactions, sound speed, single-field vs multi-field, initial quantum state, ...

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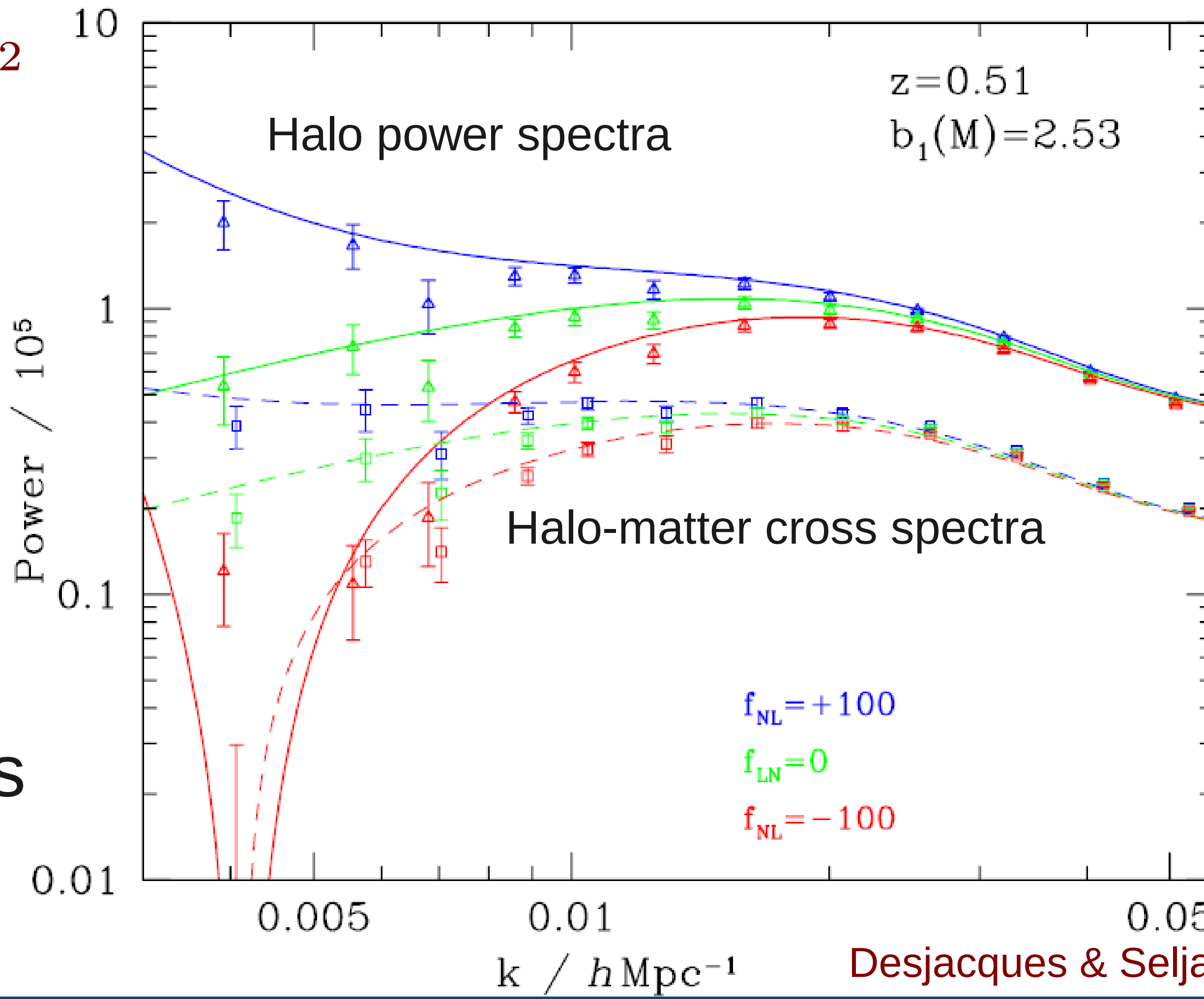
- Goal of this talk: describe how we can measure this from galaxy surveys

Motivation: Halo clustering with *local NG*

- Effect on halo power spectrum from simulations

$$\frac{\Delta P_g(k)}{P_g(k)} = 2\frac{\Delta b(k)}{b} \propto k^{-2}$$

- Current constraints from SDSS: $|f_{\rm NL}^{\rm loc}| \lesssim 90$
- Comparable to CMB constraints



Desjacques & Seljak

Statistical description

- A Gaussian field ϕ is completely described by its power spectrum:

$$\langle\phi(\vec{k})\phi(\vec{k}')\rangle = (2\pi)^3\delta_D(\vec{k}+\vec{k}')P_\phi(k)$$

  - Different Fourier modes are uncorrelated

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  - $\phi = 3\zeta/5$ Bardeen potential during matter domination = Newtonian potential on large scales

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- In non-Gaussian (NG) case, all higher point correlations non-zero
  - However, $\phi \sim 10^{-5}$ → perturbative expansion

Describing Non-Gaussianity

- Either via *bispectrum*

$$\langle\hat{\phi}(\vec{k}_1)\hat{\phi}(\vec{k}_2)\hat{\phi}(\vec{k}_3)\rangle = (2\pi)^3\delta_D(\vec{k}_1+\vec{k}_2+\vec{k}_3)B_\phi(k_1,k_2,k_3)$$

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- Or via *field redefinition*

$$\hat{\phi}(\vec{k}) = \phi(\vec{k}) + f_{\rm NL}\int\frac{d^3\vec{k}_1}{(2\pi)^3}\,\omega(\vec{k}_1,\vec{k}-\vec{k}_1)\phi(\vec{k}_1)\phi(\vec{k}-\vec{k}_1)$$

Gaussian random field

Physical, non-Gaussian field

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Amplitude parameter

"Shape"

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  - Used for initializing N-body simulations

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  – *Local model:* $\hat{\phi}(\vec{x}) = \phi(\vec{x}) + f_{\rm NL}\phi^2(\vec{x})$

$$\Leftrightarrow \omega(\vec{k}_1,\vec{k}_2) = 1$$

Large Scale Structure

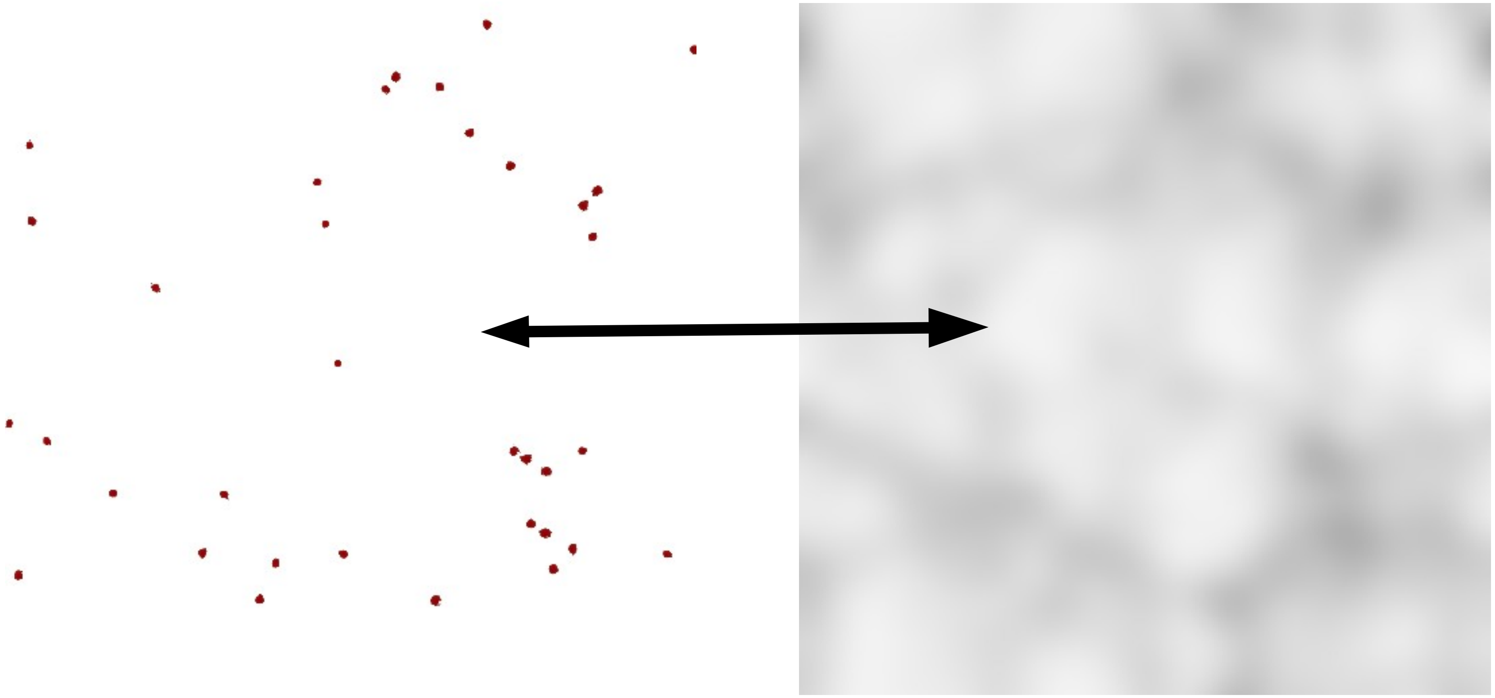
We observe this

(dramatization)

Large Scale Structure

We observe this

We want to infer this



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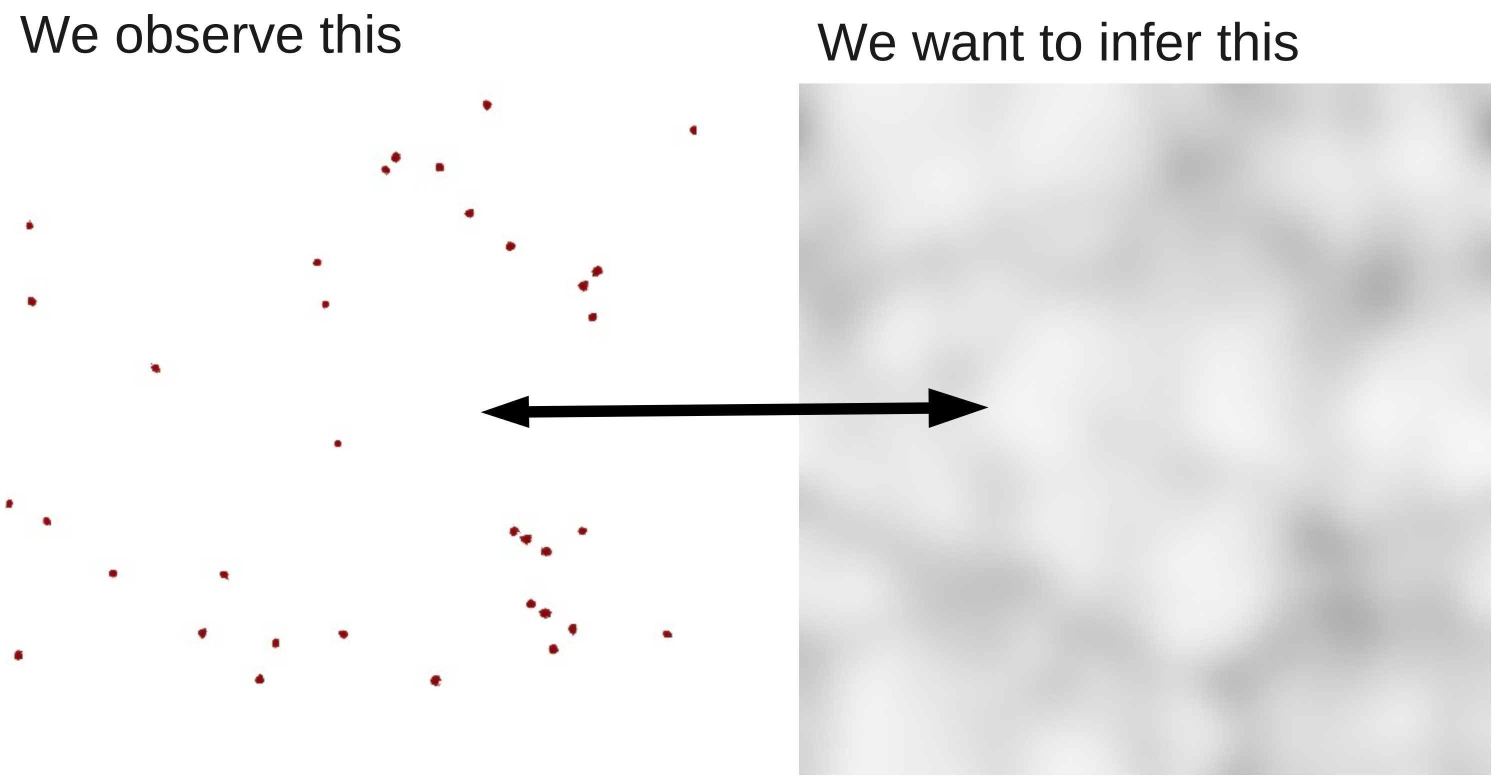

(dramatization)

- Key theoretical problem:
  - how to map *initial linear fluctuations* to observed *non-linear density field* of tracers (on large scales)

Large Scale Structure

- We need to map
  - *linear matter overdensity* $\delta = \frac{\delta\rho_m}{\bar{\rho}_m}$
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- In the following, focus on *halos:*
  - collapsed, virialized dark matter structures
  - Easy comparison with N-body simulations

Peak-Background Split (PBS)

(initial, linear)

- Write perturbations* as: $\delta = \delta_l + \delta_s, \;\; \phi = \phi_l + \phi_s, \;\; ...$

*Work in synchronous gauge

Peak-Background Split (PBS)

(initial, linear)

- Write perturbations* as: $\delta = \delta_l + \delta_s,\ \phi = \phi_l + \phi_s,\ \ldots$

“s”: scales which govern halo formation

“l”: scales on which clustering is measured

*Work in synchronous gauge

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- Definition of bias: $\boxed{b_1 = \frac{\partial \ln n_h}{\partial \delta_l} - 1}$ Lagrangian bias

n_h: halo number density per ln *M*

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  – Halo power spectrum: $P_h(k) = b_1^2 \, P(k) + ...$

corrections relevant on small scales

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  corrections relevant on small scales

  – n_h depends on $\rho_{m,l}$ and matter power spectrum

    - Simplest case: through variance on mass scale M, σ_M^2
    - assume universal mass function for explicit expressions

Halo Bias in PBS

- Large-scale δ changes collapse threshold:

$$\delta_c \to \delta_c - \delta_l \quad \Rightarrow \quad b_1 = -\frac{\partial \ln n_h}{\partial \delta_c}$$

Mo & White 96

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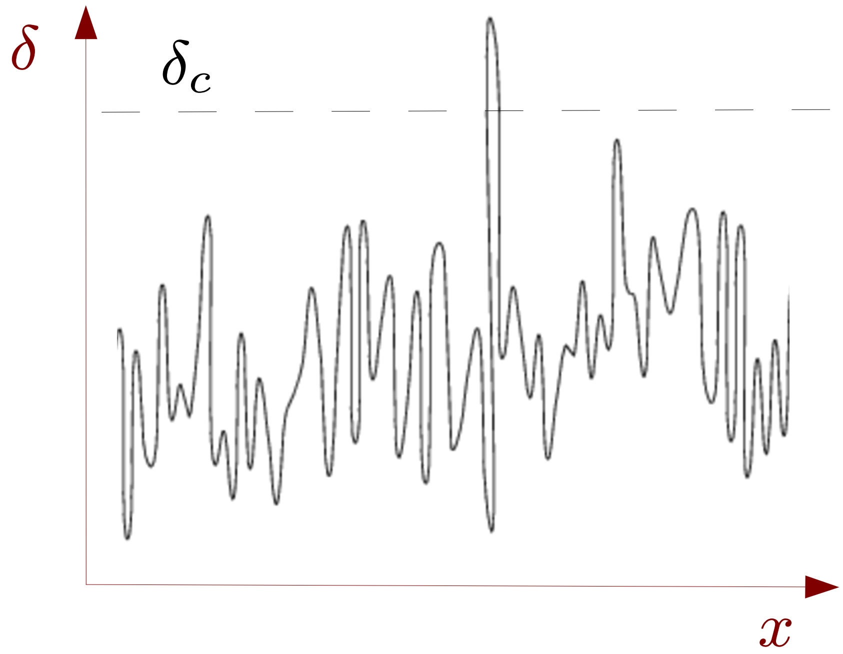

Density field smoothed on (Lagrangian) scale of halos

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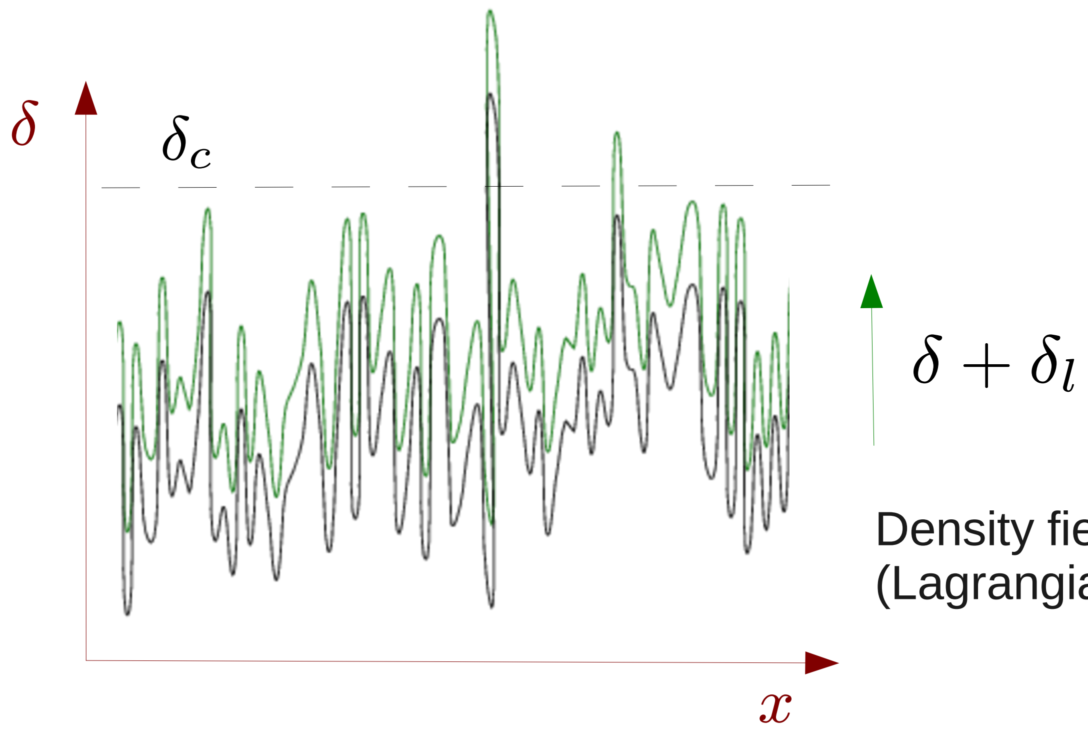

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Non-Gaussianity and PBS

- Consider local non-Gaussianity:

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- Small-scale density field is rescaled by (long-wavelength) potential perturbations
  - Variance on mass scale M:

$$\hat{\sigma}^2_M(\vec{x}) = \sigma^2_M[1 + 4f_{\mathrm{NL}}\phi(\vec{x})]$$

Dalal et al,
Slosar et al

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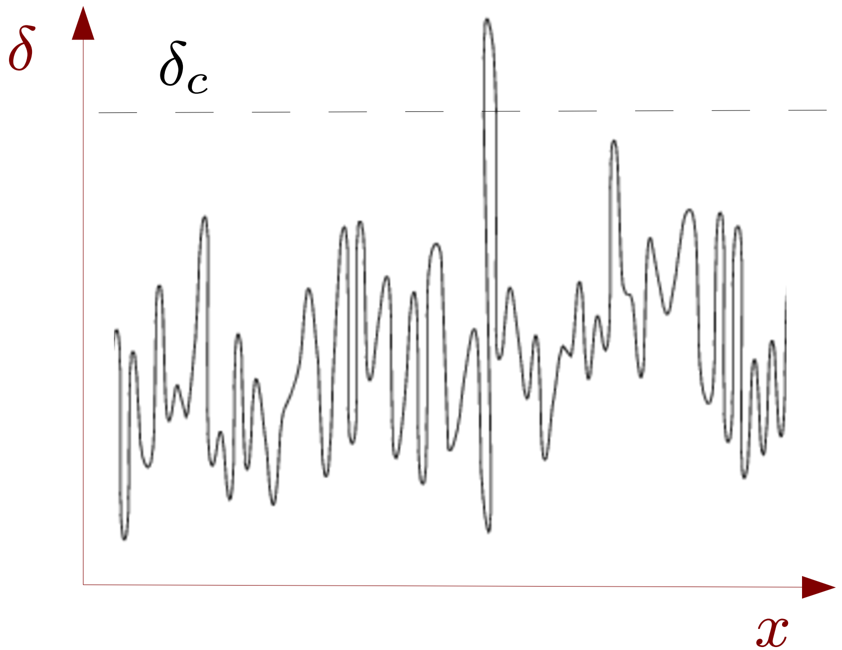

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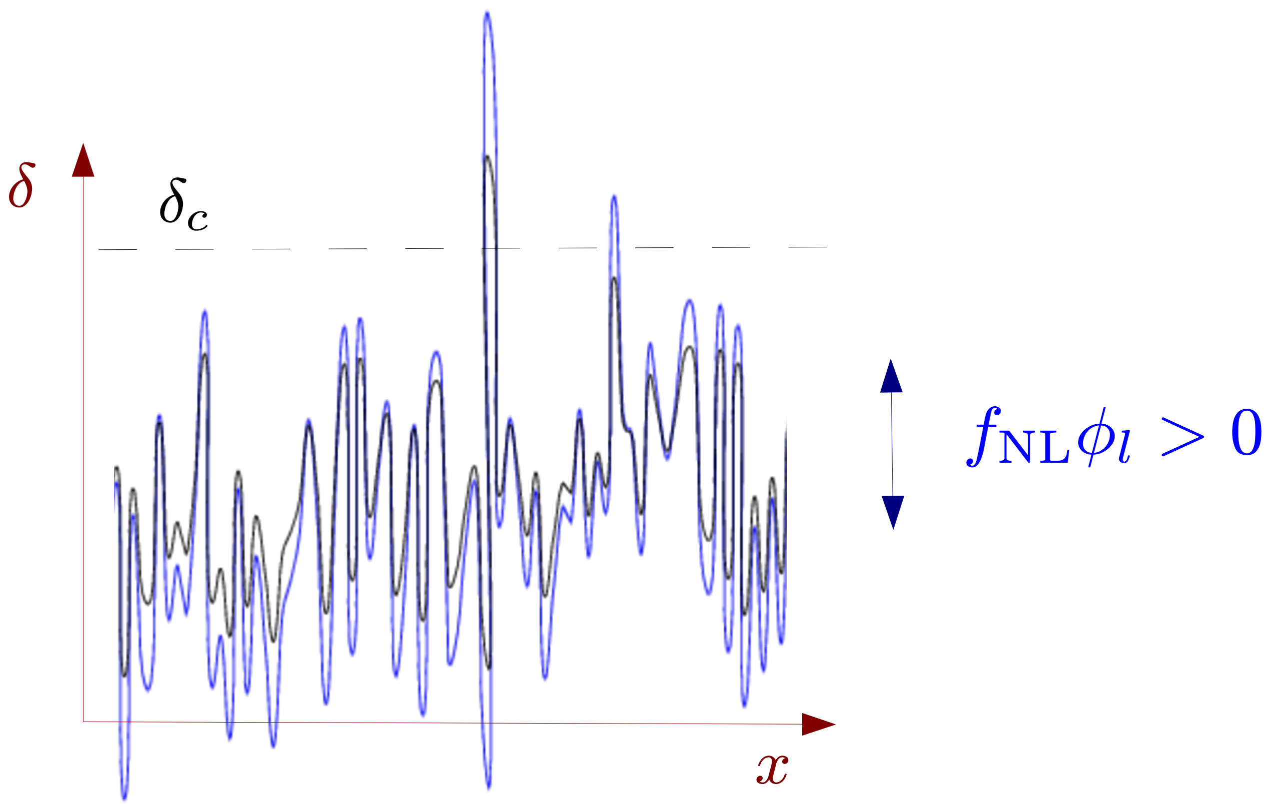

General quadratic NG

- Straightforward to generalize for any quadratic non-Gaussianity:

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FS & Kamionkowski

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$$\sigma^2_{\omega M}(k) \equiv \int \frac{d^3 k_s}{(2\pi)^3} \, \omega(\vec{k}, \vec{k}_s) W^2_M(k_s) P(k_s)$$

Tophat filter of scale *M*

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Tophat filter of scale *M*

  - Note: coupling of potential with density in general depends on *k* and *M*

FS & Kamionkowski

Non-Gaussian halo bias

- Just a matter of chain rule...
  - In standard formalism, $n_h = n_h(\rho_m, \sigma_M)$,

$$b_1 = \frac{\partial \ln n_h}{\partial \delta_l} - 1$$

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$$\mathcal{M}(k) = \frac{2}{3} \frac{k^2 T(k) g(z)}{\Omega_m H_0^2 (1+z)}$$

FS & Kamionkowski

Predictions for Δb

- Scale-invariant bispectra: $\omega(\vec{k}_s, \vec{k}) = C\,(k/k_s)^n$
- Examples:
  - *Local model:* $\omega \to 1 \Rightarrow \sigma_\omega^2 = \sigma_M^2 \Rightarrow \Delta b_1 \propto k^{-2}$
  - *Equilateral form:* $\omega \propto k^2 \Rightarrow \Delta b_1 \approx \mathrm{const.}$
  - *Folded form:* $\omega \propto k \Rightarrow \Delta b_1 \propto k^{-1}$

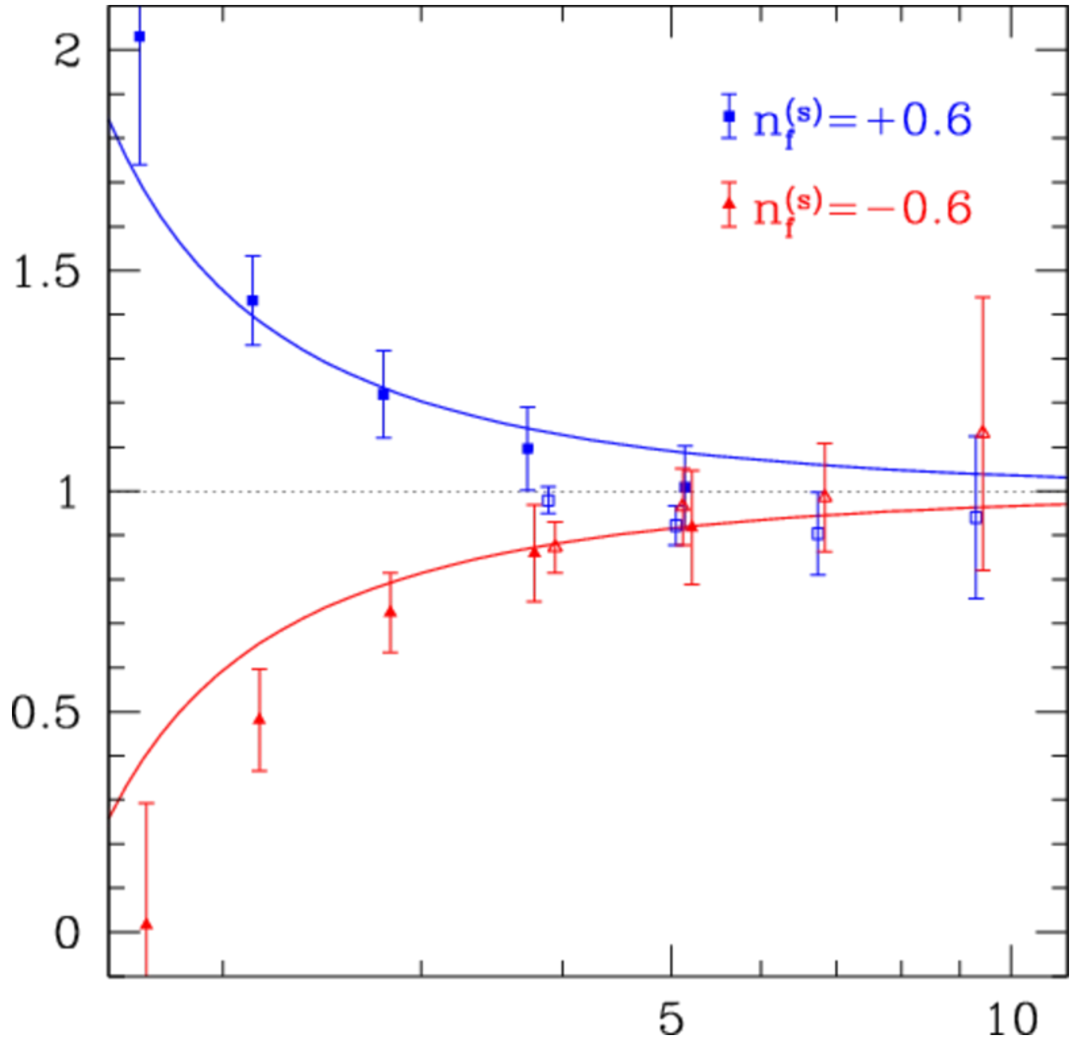
Technical detail

- So far, considered effect of NG on $\nu = \delta_c/\sigma_M$
- Also have to take into account effect on Jacobian $\frac{d \ln \nu}{d \ln M}$ (since we identify halos by mass, not by ν)
- Yields additional term in Δb, $\propto \frac{\partial \ln \sigma^2_{\omega\ M}(k)}{\partial \ln M}$
- Order unity effect for non-local types of NG !

Desjacques, Jeong, FS (2011)
Scoccimarro et al (2011)

Updated PBS predictions

- Scale-dependent local model

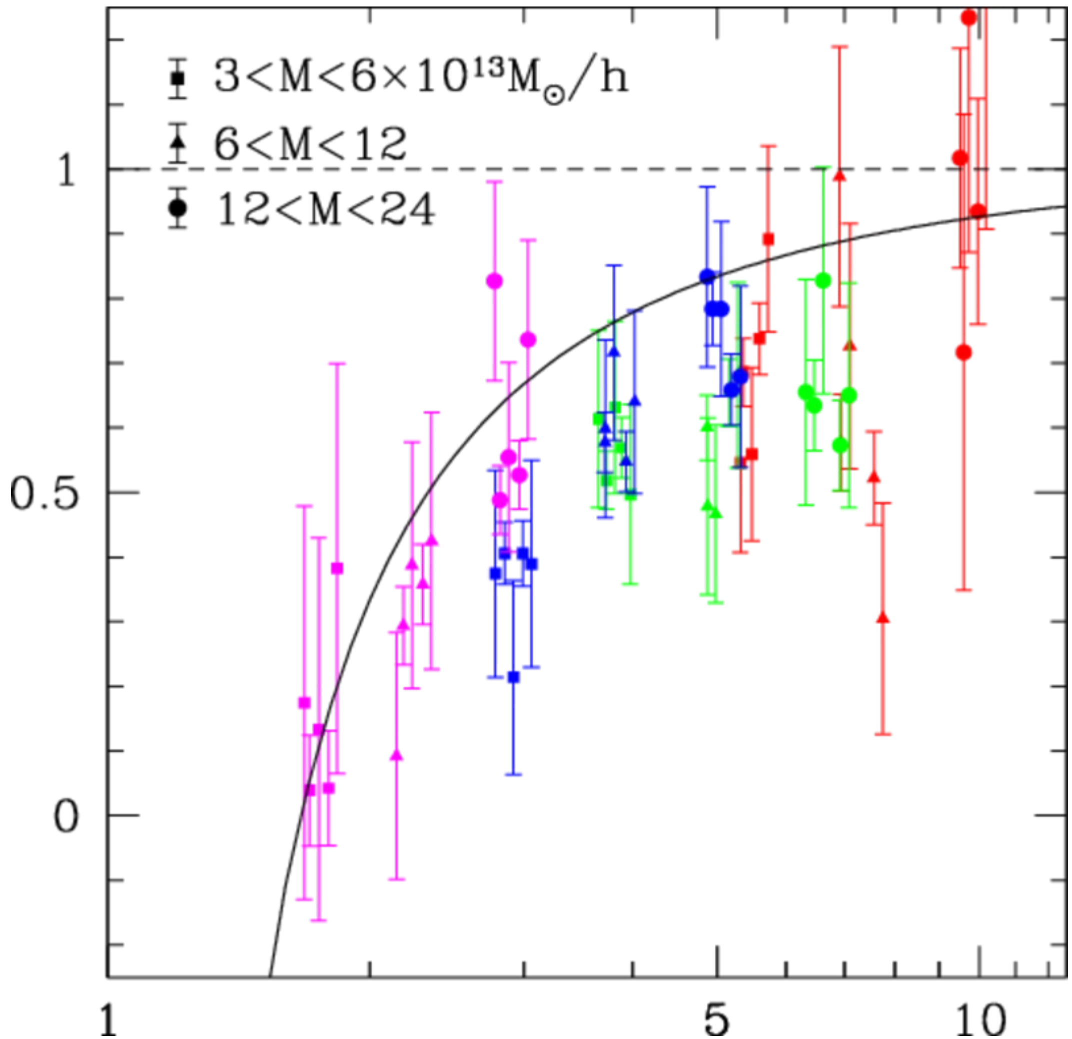


Ratio of simulations / new predictions to previous PBS prediction

Desjacques, Jeong, FS (2011)

Updated PBS predictions

- Folded/orthogonal model



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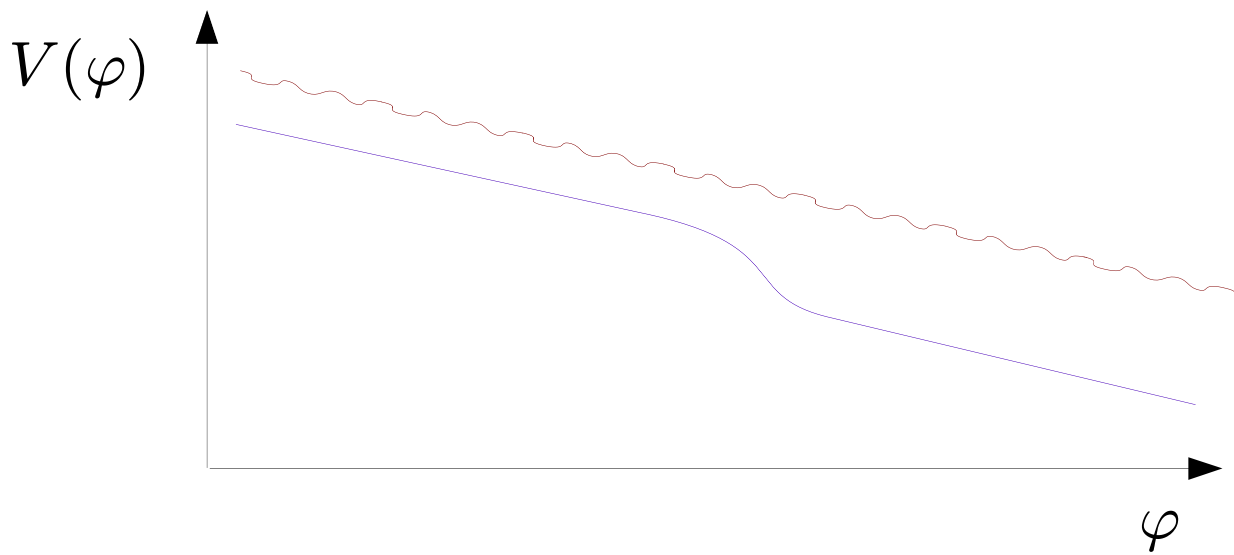
More “interesting” examples...

- Strongly scale-dependent non-Gaussianity
  - Due to periodic modulation of, or feature in inflaton potential
  - *Violating “slow-roll”:* small effects on P(k), but large non-Gaussianity (in standard single-field inflation !)



Cyr-Racine & FS, 2011

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- Mode coupling depends strongly on k_s:

$$\omega(k, k_s) \stackrel{k_s \gg k}{=} F(k_s)$$

  - Scale-dependence as in local model*: $\Delta b \propto k^{-2}$

** Gauge issues in squeezed limit still to be worked out*

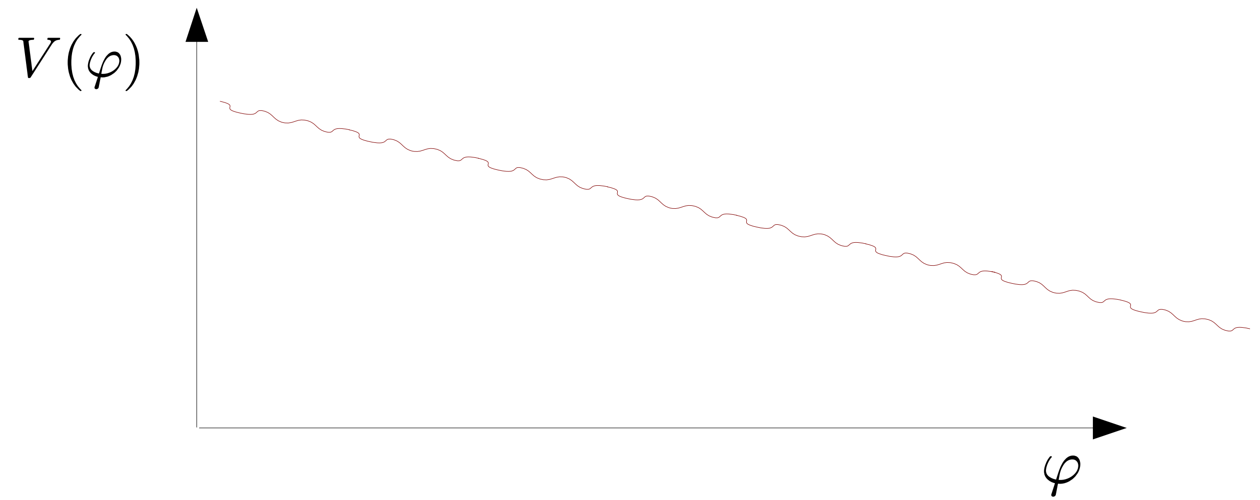
Cyr-Racine & FS, 2011

Resonant Non-Gaussianity

- Periodic modulation of inflaton potential
  - Modes pass through resonance while sub-horizon
  - $\omega(k, k_s) \propto \sin\left(C_\omega \ln k_s / k_*\right)$

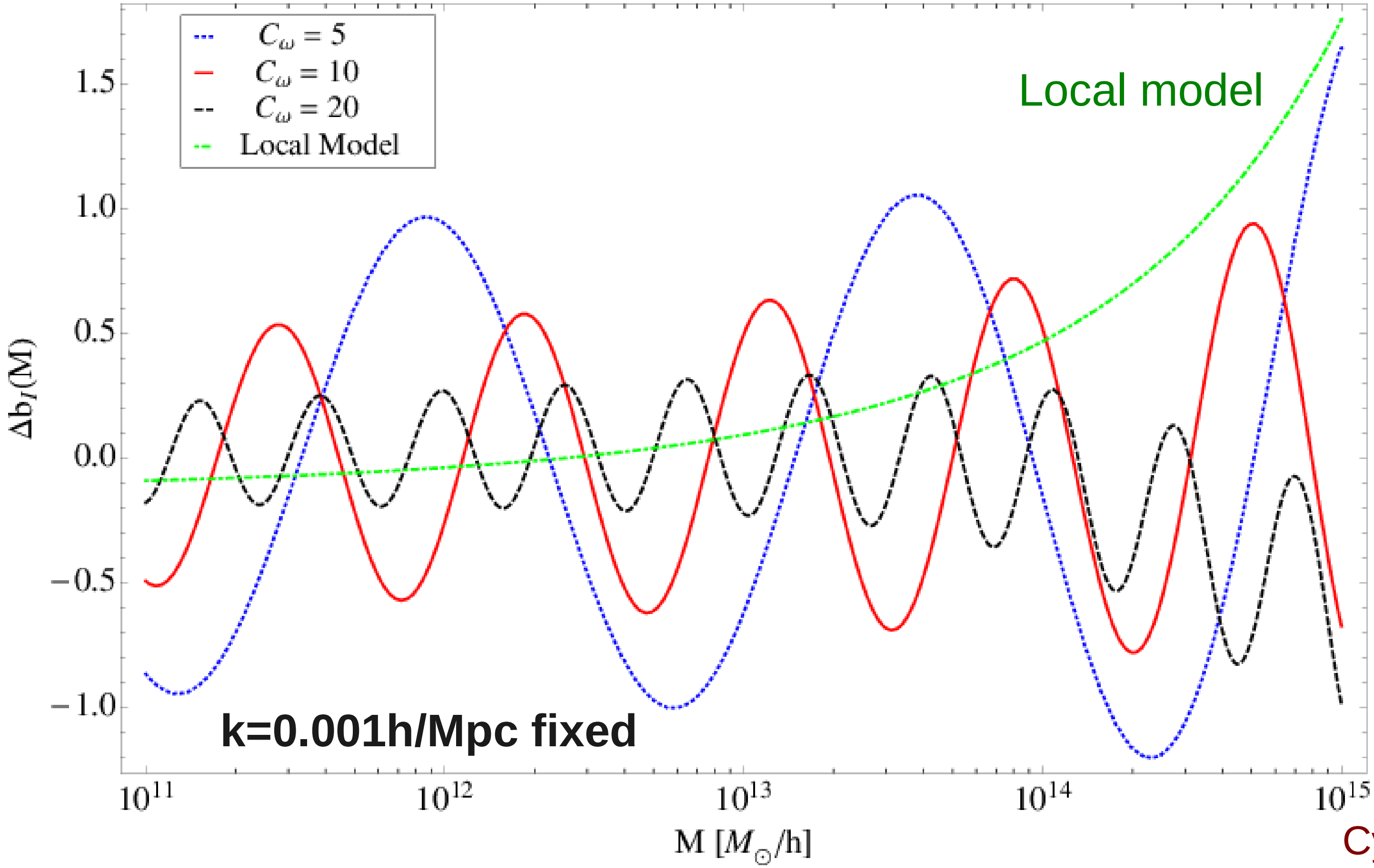
Flauger & Pajer

- Consider models that pass current CMB constraints



Resonant Non-Gaussianity

- Δb as function of halo mass
  - Oscillations in *mass-dependence* of galaxy clustering



New term from Jacobian crucial

Cyr-Racine & FS, 2011

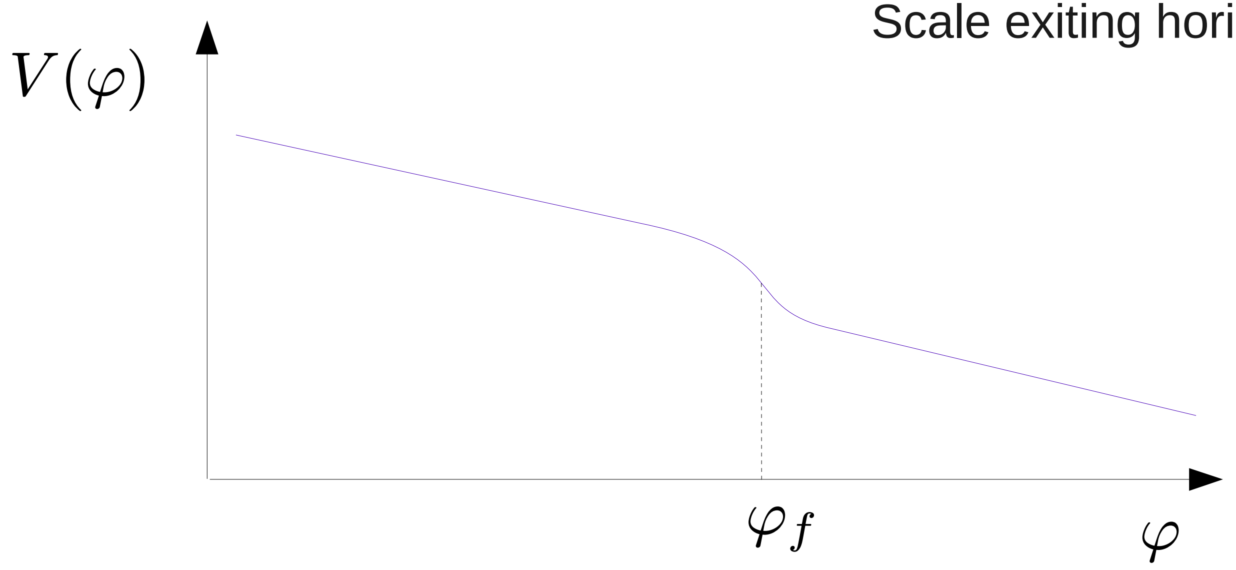
Feature in Inflaton Potential

- Bump or step in the potential generates non-Gaussianity

X. Chen et al

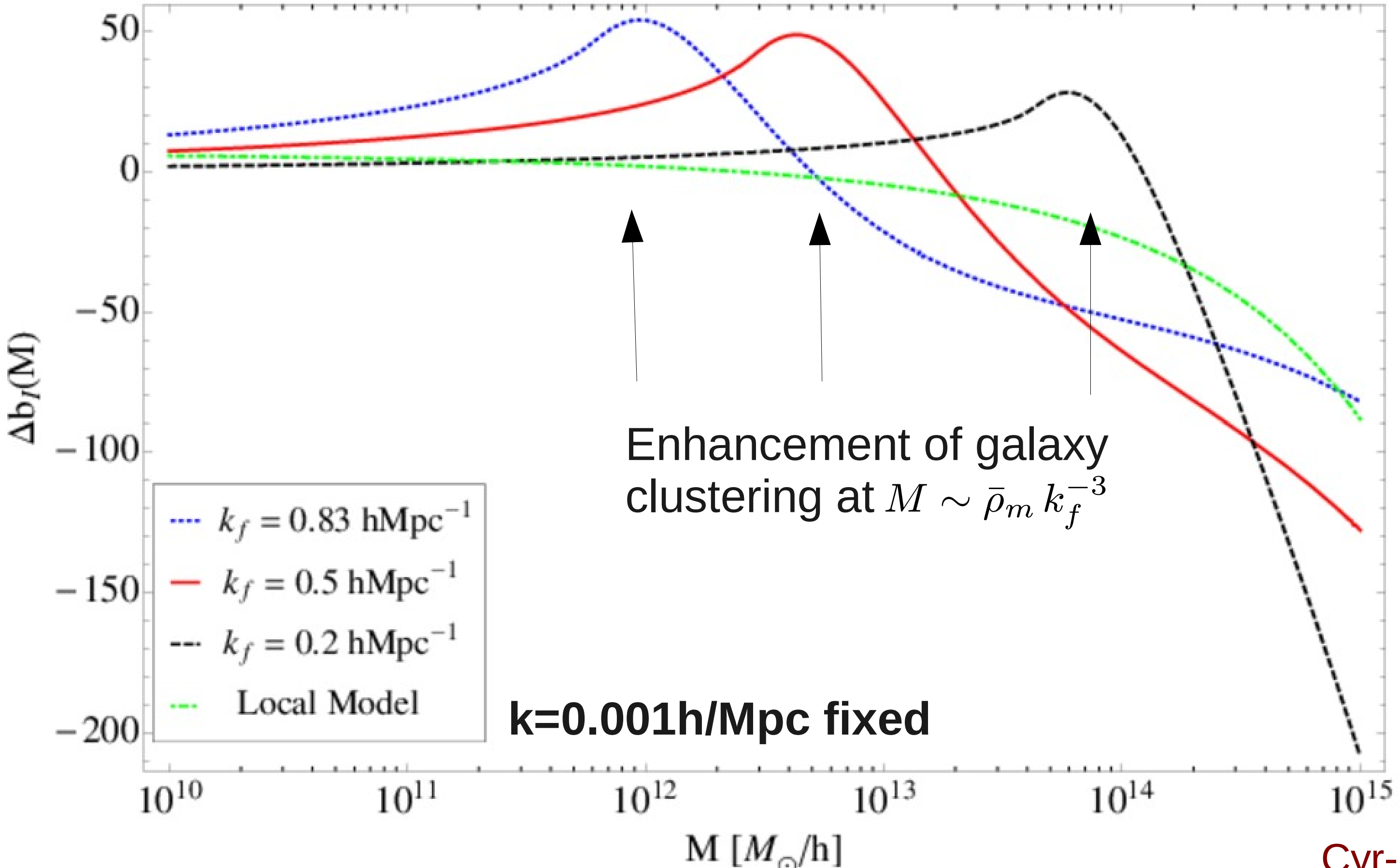
  - temporarily breaking slow-roll
  - $\omega(k, k_s) \propto \sin k_s/k_f$

Scale exiting horizon when inflaton crosses feature



Feature in Inflaton Potential

- Δb as function of halo mass
  - Feature appears at mass scale $M \sim \bar{\rho}_m k_f^{-3}$



Constraints on k_f complementary to CMB

Cyr-Racine & FS, 2011

Galaxy clustering in relativistic context

- Scale-dependent bias $\propto (k/H)^{-2}$ raises issue of relativistic corrections
- Covariant expression for galaxy density (three-form) simplifies in synchronous gauge
  - Equal time hypersurface = constant-age hypersurface

$$N = \int_{V_{\rm obs}} \sqrt{-g}\, n_g(x^\alpha_{\rm true}) \frac{1}{a(x^0_{\rm true})} \left| \frac{\partial x^i_{\rm true}}{\partial x^j_{\rm obs}} \right| d^3x_{\rm obs}$$

Yoo et al, 2009
Challinor & Lewis 2011
Baldauf et al 2011
Jeong, FS, Hirata 2011

Galaxy clustering in GR

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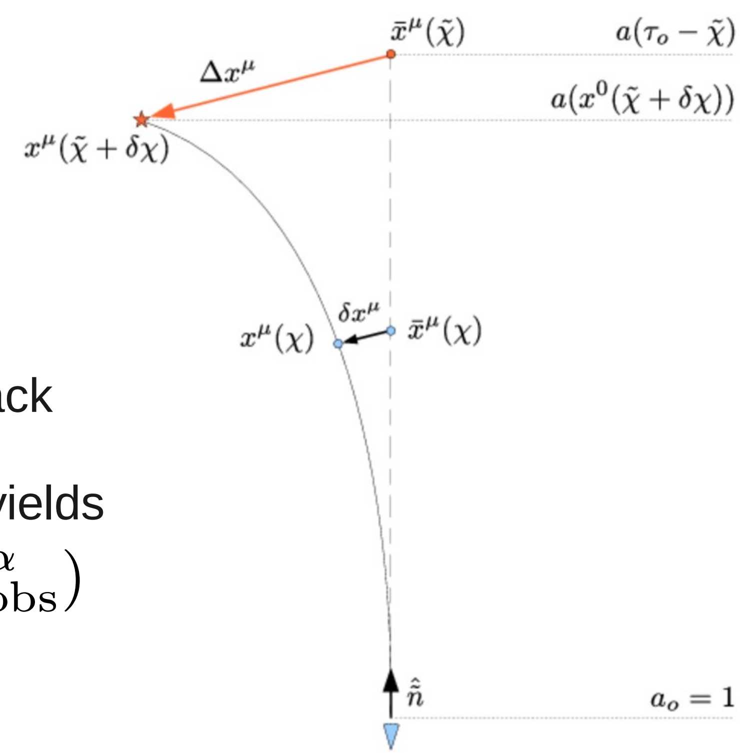
Volume distortion

Deflection

Intrinsic galaxy density



Tracing back perturbed geodesic yields $x^\mu_{\rm true}(x^\alpha_{\rm obs})$

Galaxy Bias

- Usually assumed on large scales: $\delta_g(\vec{x}) = b\,\delta_m(\vec{x})$
  - Linear, local bias

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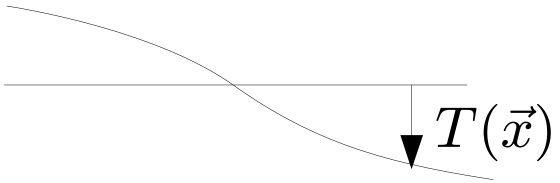
$$\delta_g = n_g/\bar{n}_g - 1$$

$$\tau \to \tau + T :$$



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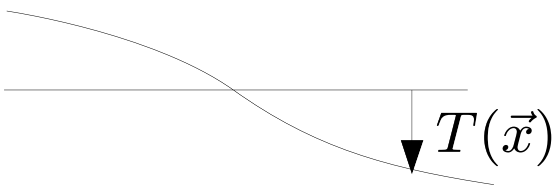

$$\tau \to \tau + T:$$

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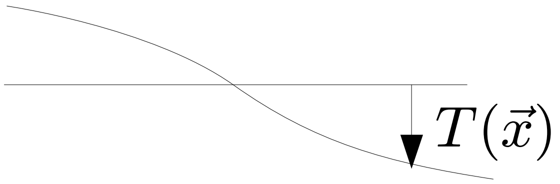

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Depends on galaxy sample

- In *what gauge* is galaxy bias linear ?

Galaxy Bias

- On large scales, galaxies can know about
  - Local matter density
  - Local age of Universe (linear growth factor)

Jeong, FS, Hirata 2011

Galaxy Bias

- On large scales, galaxies can know about
  - Local matter density
  - Local age of Universe (linear growth factor)
- Hence, $\delta_g \propto \delta_m$ on constant-age slices
  → synchronous gauge
  - Gauge-invariant expression for galaxy density perturbation:

$$\delta_g = b(\tau)[\delta_m - 3aH\delta\tau] - b_e(\tau)aH\delta\tau$$

Perturbation in conf. time
w.r.t. constant-age slice

Jeong, FS, Hirata 2011

NG halo bias in GR context

- With NG initial conditions, different areas of the Universe at same age have different power spectra

Jeong, FS, Hirata 2011

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Jeong, FS, Hirata 2011

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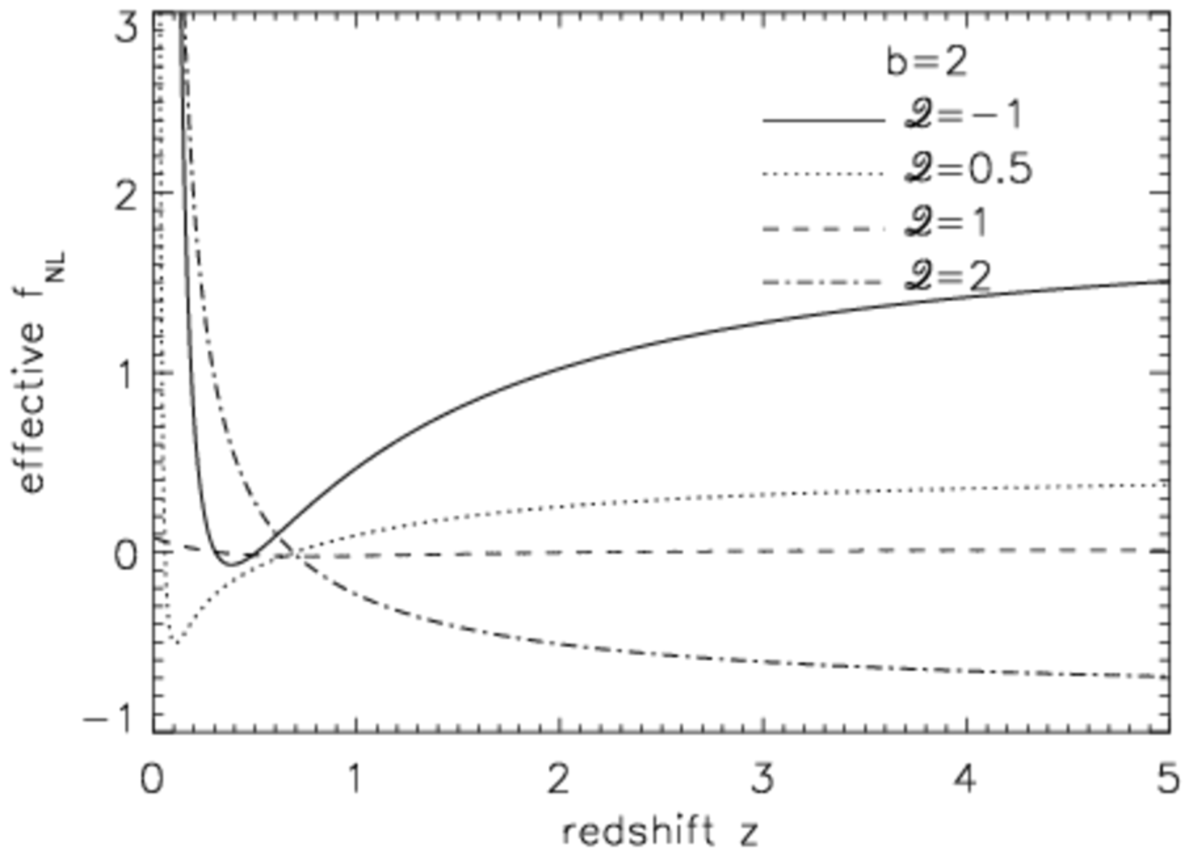
- Additional terms from volume distortions, redshift perturbations, … comparable to effective $f_{\rm NL,eff} \lesssim 2$

Jeong, FS, Hirata 2011

NG halo bias in GR context

- Effective f_{NL} from GR corrections



$$\mathcal{Q} = 5s/2$$

Magn. bias amplitude

Jeong, FS, Hirata 2011

Other ways to look for NG ?

- Why not lensing ?
  - Lots of information in shear maps

Other ways to look for NG ?

- Why not lensing ?
  - Lots of information in shear maps
- Lensing estimators not perfectly linear:

$$\hat{\gamma} = \gamma + b\,\kappa\;\gamma + \ldots \qquad \hat{\kappa} = \kappa + c\,\kappa^2 + d\,|\gamma^2| + \ldots$$

  - Lensing power spectra receive contribution from primordial NG:

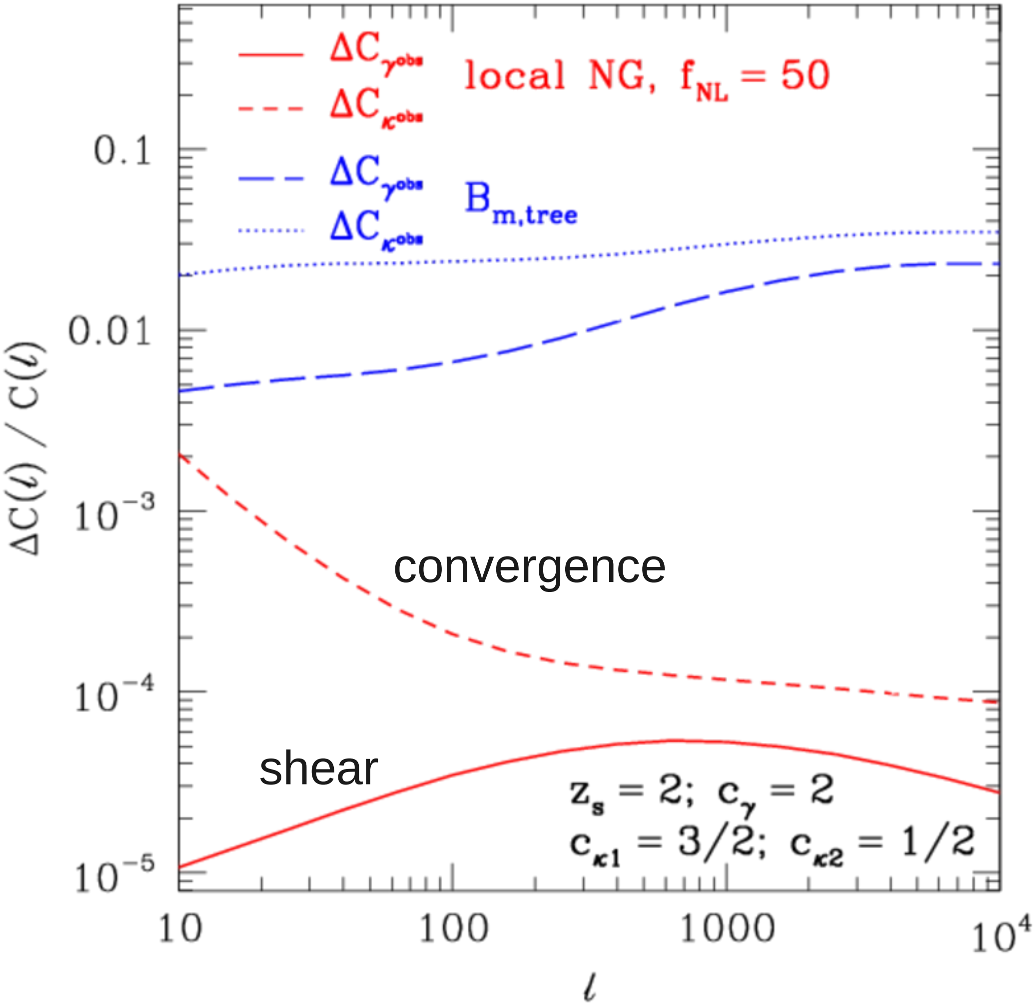
$$\Delta C^{\kappa\kappa}(\ell) \propto \int \frac{d^2\ell_1}{(2\pi)^2} B_\kappa(\ell_1, |\vec{\ell} - \vec{\ell_1}|, \ell) \times (\text{geometric factors})$$

κ bispectrum in squeezed limit
- projection of matter bispectrum

Jeong, FS, Sefusatti 2011

NG with Weak Lensing

- Unfortunately, effect is very small...



Relative magnitude of contributions to lensing power spectra

From tree-level bispectrum (gravitational collapse)

From local primordial NG

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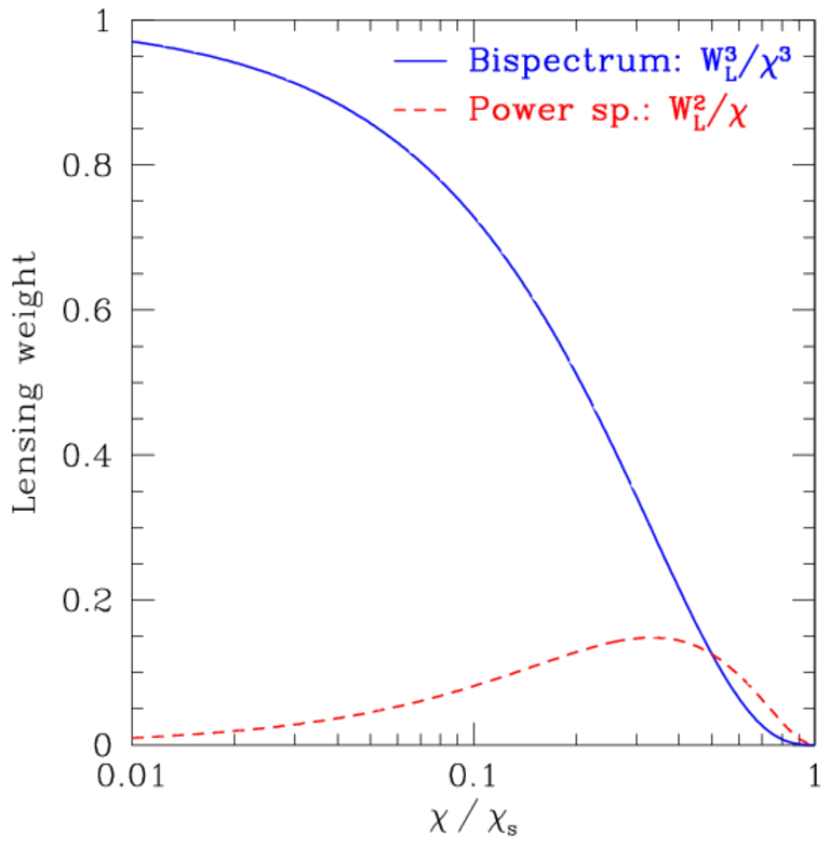
NG with Weak Lensing

- Two very basic, generic reasons:
  1) Projection favors low redshifts → small scales



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NG with Weak Lensing

- Two very basic, generic reasons:
  1) Projection favors low redshifts → small scales
  2) Central limit theorem: effect is suppressed by

$$\boxed{L_p/\Delta\chi}$$

$\Delta\chi \sim \mathrm{Gpc}$ width of projection kernel

$$L_p \equiv \int \frac{d^2k}{(2\pi)^2} P(k) \approx 75\ \mathrm{Mpc}$$

1D coherence length of matter density field

Jeong, FS, Sefusatti 2011

NG with Weak Lensing

- Two very basic, generic reasons:
  1) Projection favors low redshifts → small scales
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- These apply to *any non-linear tracer of any projected density field*
  - E.g. shear peaks, IR/UV backgrounds, ...

Jeong, FS, Sefusatti 2011

Summary

- Galaxy clustering offers rich possibilities for testing inflation through non-Gaussianity
  - Scale-dependent bias: non-trivial *k- and M-* dependence
  - Complementary to CMB
  - NG halo bias on large scales now understood, including GR corrections
  - More work needed for smaller scales...
- On the other hand, weak lensing (in itself) is not a promising probe of NG

And sorry for not talking about primordial gravity waves...